Final Document:
Fast, Compact, High Strength Magnetic Pulse Generator

MAY 15-30

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1 CONTENTS

1. SYSTEM LEVEL DESIGN

1.1 SUMMARY OF DEVICE

As communication technology utilizing new magneto-optic materials advances, there becomes and increased need for small-scale, high-powered magnetic field generators. Although a single-coil field generator design is not a new area, few applications require small devices with such high current requirements at high speeds. With this said, little research has been done to create such a device. This senior design project presents a magnetic field generation circuit to be used in a research-grade fiber-optic switch with magneto-optic material.

This document covers the overall design, strategy, functionality, applications, and results of this magnetic pulse generator project.
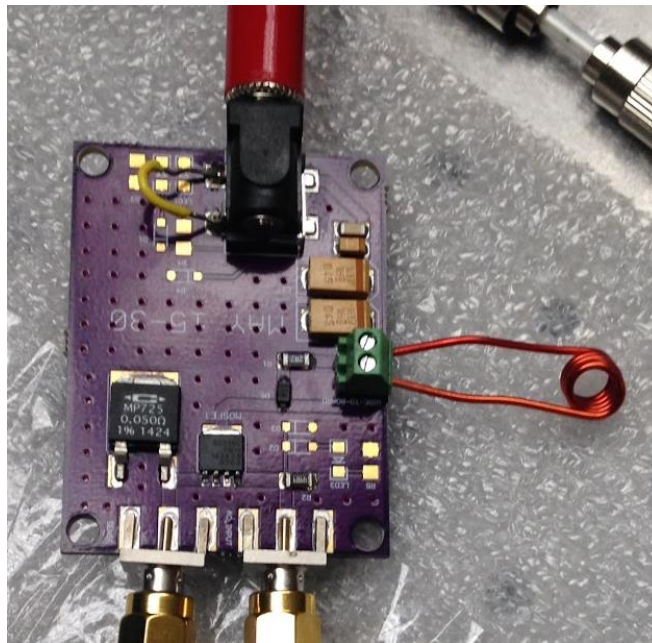

Figure 1: Electromagnetic Pulse Generator Prototype

1.2 PROJECT REQUIREMENTS

1.2.1 FUNCTIONAL REQUIREMENTS

- The device shall generate a magnetic pulse of 500 gauss or greater.
- The duration of the pulse shall be one microsecond.

1.2.2 NON-FUNCTIONAL REQUIREMENTS

- The device shall be in an enclosure-ready.
- The device shall have a DC source voltage of 15 volts or less.
- The device shall not exceed the dimensions 3.5" (L) x 2.0" (W).

1.3   FUNCTIONAL DECOMPOSITION

1.3.1 POWER SUPPLY

Our design calls for the use of two power supplies. One DC power supply and one pulse generator. The DC power supply will provide the current for energizing the coil. We will have the power supply to the coil set at 15 volts. This will power the capacitors that drive the current through the coil.

Our second power supply is a pulse generator. This power supply acts as a trigger for our MOSFET. It will send a five volt pulse every one microsecond.

1.3.2 ENERGY STORAGE

Capacitors near the DC voltage input hold a charge and effectively reduce the time it takes for the current to pass through the coil. Using our present calculations for the current and voltage, we have decided to use four capacitors of values .01µF, .1µF, and two 100µF. The equations below gave us a minimum (base) value we could use for the total capacitance. This equation assumes that we have 25 Amps of current in our inductor and a pulse width of one microsecond.

$$\frac{Current * Pulse\ Width}{Voltage} = Capacitance$$

$$\frac{25\frac{Coulomb}{second} * 1 * 10^{-6}seconds}{15\ Volts} = 1.67 * 10^{-6}Farads$$

For a circuit like ours, it is common practice to take this minimum value and multiply it by 100 or more. Our total capacitance used in our circuit is 200.11uF, which is roughly 120 times larger than our base value. The .1µF and 100µF capacitors we are using are tantalum capacitors because of their lower internal resistance while the 0.01µF capacitor was ceramic due to the cost and availability of a tantalum capacitor that small.

1.3.3 ENERGY DISSIPATION

A 2Ω resistor in series with the diode is placed in parallel with the wire-to-board connector. This is because without the resistance, the current would continue to loop between the coil and

diode because there is no place for the energy to dissipate. OrCAD makes all wire resistances ideal (zero), thus we may not need this 2Ω resistor in our physical circuit. The wires and connections may cause enough resistance for this energy to dissipate elsewhere.

Our design also contains a current sense resistor with a value of 0.05Ω. Due to the difficulty of measuring the magnetic field our coil can output, the current sense resistor will allow us to measure the drain current which should theoretically match the current going through the coil. For example, if we are expecting to use 20-25A, we should expect to see a 1.00-1.25V drop across the resistor, thus changing our gate-to-source voltage from 5V to 3.75-4.00V. It is something we need to account for, and ideally the resistor would not be a part of our circuit. It is first and foremost for testing purposes.

1.3.4 SWITCHING DEVICE

Through preliminary simulation, we were able to determine that our MOSFET was going to need to handle at least 65 amps of pulsing current. Most importantly, this MOSFET meets a number of design specifications:

- Drain to Source Voltage (VDS) must be able to handle 15V or more
- Current channel must be able to handle the current load through the coil
- Surface mount component
- Fast switching
- N- channel, operates using a positive input voltage and faster switching
- Suited for high switching frequencies resulting in a soft-recovery
- Low parasitic inductance and resistance
- VDS rated up to 30 V
- Pulsed, peak drain current rated up to 1888 A

EMF voltage occurs when the waveform generator goes from its upper voltage to lower voltage. In EMF voltage, the change in current over the change in time becomes negative. The inductance doesn't change, hence giving a negative voltage across the coil. Because the change in time will be very small, the magnitude of the negative voltage will be very large. Without a diode, this large negative voltage will reach the MOSFET and potentially ruin the MOSFET. We have chosen a large diode in parallel to the coil that prevents back EMF into the MOSFET. Specifications include:

- Fast recovery time
- High reverse breakdown voltage

- Surface mount component

1.3.5 COIL

The coil is a necessary part of the circuit as explained by Faraday's Law whereby a current passing through a coil will generate a magnetic field. The current is also directly proportional to the magnetic field, so to increase the magnetic field to 500 gauss, we wanted our circuit to be able to handle a higher currents. The magnetic field is generated at the center of the coil as shown in Figure 2.
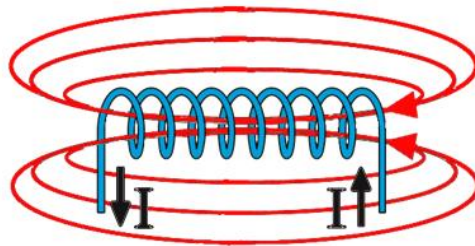
Figure 2: Magnetic Field Generation

During our research and simulations, we found that having a low inductance was also important. The lower the inductance of the coil, the faster the rise and fall time of our pulse width would be. In order to achieve low inductance in the coil, we looked at what parameters (length, number of turns, etc.) we could change. We reviewed equations: $B = \frac{\mu NI}{\sqrt{l^2+4R^2}}$ and $L = \frac{\mu N^2(\pi R^2)}{\sqrt{l^2+4R^2}}$ and found that the number of turn of the coil was a parameter that impacted both the current and the inductance (the two most important parameters for a strong field and fast pulse.)

We decided to create a MATLAB script (that can be found in Appendix E) to plot these parameters as shown below in Figure 3.
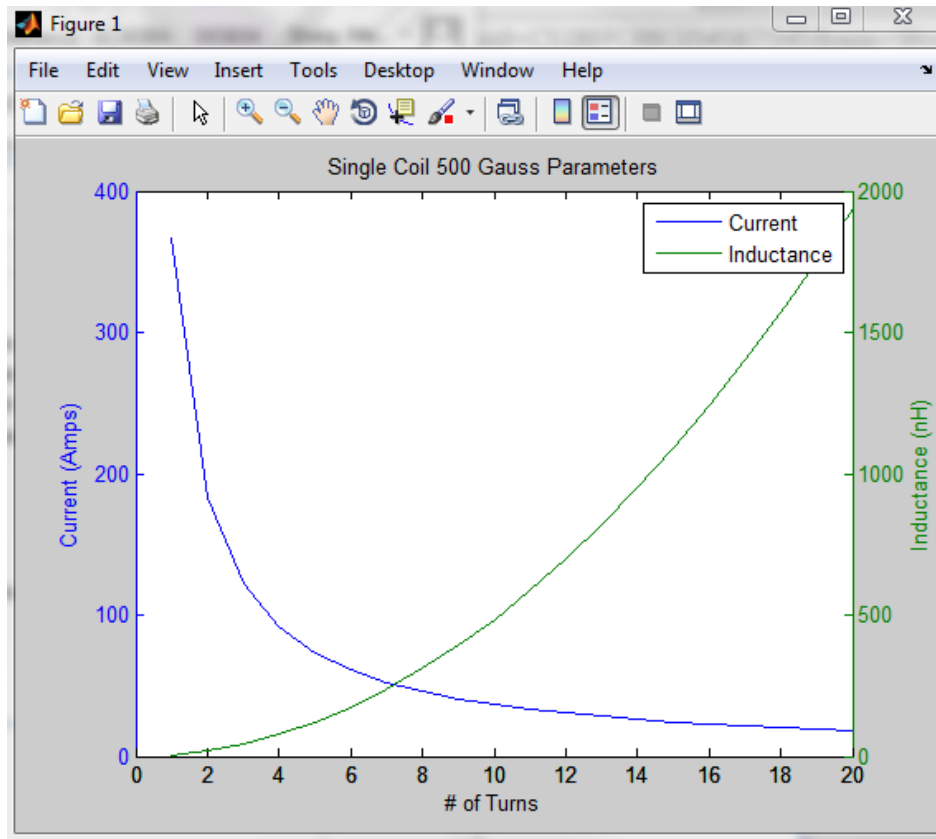
Figure 3: Single Coil Parameters at 500 Gauss (Current and Inductance vs. Number of Turns of the Coil)

As shown, as the numbers of turns increases, the current decreases and the inductance increases. From this we knew that we wanted a fairly small number of turns in our coil. For a single coil, somewhere around 5 turns would give us a high enough current to produce 500 gauss and not fry our components while giving us a small enough inductance to meet our pulse width speed requirements.

The resistance affects the functionality of the coil as well. The resistance lowers the current, which also lowers the magnitude of our magnetic field; therefore, the lower the resistance of the coil, the easier it is for the magnetic field to reach 500 gauss. Our team did a test by measuring the resistance of a five turn coil with an Agilent 4263 Model B LCR meter and measured resistance at 0.084Ω. Based on this, we expect the final resistance of the coil to have little impact on the final design.

1.3.6 SINGLE COIL VS. HELMHOLTZ COIL
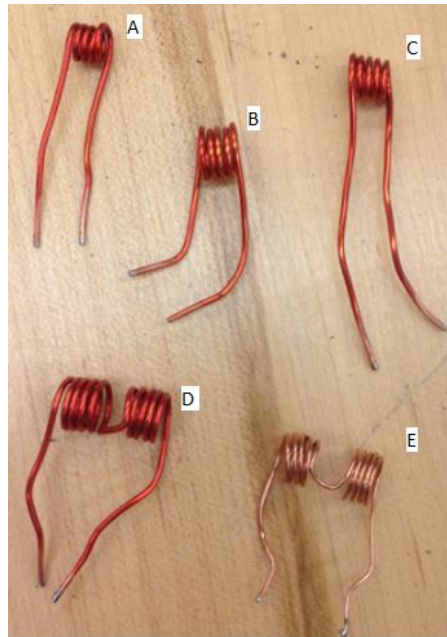
	Coil A	Coil B	Coil C	Coil D	Coil E
Frequency	Inductance (nH)	Inductance (nH)	Inductance (nH)	Inductance (nH)	Inductance (nH)
0.5 MHz	73.81	134.01	113.41	294.91	329.01
1 MHz	59.93	119.93	102.83	289.23	307.33
1.5 MHz	68.62	126.22	111.02	282.22	305.42
2 MHz	67.21	124.81	106.91	280.91	296.41

Figure 4: Single and Helmholtz Coils

Two different types of coils with dissimilar properties were chosen to use throughout the course of the project: a single coil and a Helmholtz coil. We tested both to see which yielded the best results and decided on the single coil configuration. There is a definite trade-off between a single and a Helmholtz coil. While a Helmholtz coil configuration generates a more powerful magnetic field with the same coil parameters and same current, the single coil has less inductance. We have calculated possible coil dimensions including theoretical inductances for both a Helmholtz coil and a single coil configuration. When constructing coils, we use a 6mm diameter (3 mm radius) coil. The length of a five turn coil is close to 1 mm in length. Below are the coil calculations for each of type of coil. Ultimately, speed of our pulse width is very important, and we decided to choose the single coil design.

1.3.7 SINGLE COIL CALCULATIONS

We calculated the magnetic field for a single coil using the equation below:

$$B = \frac{\mu NI}{\sqrt{l^2 + 4R^2}} = \frac{(4\pi \times 10^{-7})(5)(48.41)}{\sqrt{(1x10^{-3})^2 + 4(3x10^{-3})^2}} = 0.050006 \, Teslas = 500.05 \, gauss$$

Coil inductance for the single coil is found using the following equation:

$$L = \frac{\mu N^2(\pi R^2)}{\sqrt{l^2 + 4R^2}} = \frac{(4\pi \times 10^{-7})5^2(\pi * (3 \times 10^{-3})^2)}{\sqrt{(1 \times 10^{-3})^2 + 4(3 \times 10^{-3})^2}} = 146nH$$

1.3.8 HELMHOLTZ COIL CALCULATIONS

The magnetic field for a Helmholtz coil is found by using equation below:

$$B = \frac{\mu(0.7155)NI}{R} = \frac{(4\pi \times 10^{-7})(0.7155)(5)(33.37)}{(3 \times 10^{-3})} = 0.050006 \, Teslas = 500.06 \, gauss$$

Coil inductance for Helmholtz coil is found using the equation below:

$$L = 2\mu(0.7155)N^2\pi R = 2(4\pi \times 10^{-7})(0.7155)5^2(\pi(3 \times 10^{-3})) = 423.7nH$$

2 DETAILED DESCRIPTION/IMPLEMENTATION DETAILS

2.1 SYSTEM DESCRIPTION

Figure 5 shows a block diagram of the concept of our design. This outlines the process of taking a pulse generator and sending a one microsecond pulse to a MOSFET. The MOSFET then switches on, causing a DC current to be drawn through the coil. In accordance with Faraday's law, the current driven through the coil will generate a magnetic field. The current sense resistor (CSR) is in place strictly for measurement purposes. The current going through the CSR is nearly equivalent to the current going through the coil. From there, we are able to see the voltage output via the oscilloscope. The voltage is measured across the 0.05Ω CSR as well as the pulse width. Utilizing the output voltage and the resistance (0.05 Ω), we can calculate the current. Once we have the current value, we use the can use the magnetic field strength equation to find the strength of the magnetic field generated.
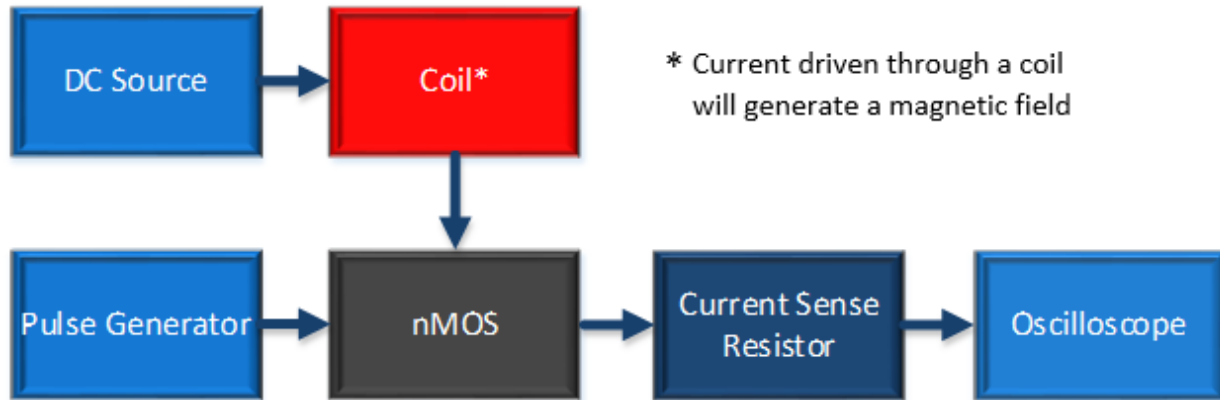
Figure 5: System Description

2.2 USER INTERFACE

The circuit can be used in a variety of setups depending on the coil. Shown below in Figure 6 is an example of how our circuit was used in our client's Sagnac interferometer setup. The coil is placed over a small tube that has a magneto-optic material located inside that can have its polarization changed depending on the various parameters for the circuit. For more information, view the User Manual in Appendix A.
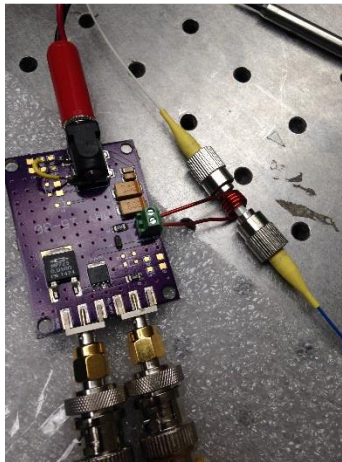
Figure 6: Interferometer Setup

2.3 FABRICATION METHODS

In creating the first version of prototypes, a PCB prototyping milling machine called the ProtoMat S62 was used to cut out boards for quick prototyping. Soldering done on the first versions of prototypes was done by hand.

For the final design, a GERBER file containing all the information needed to fabricate a board was sent to OSHPark for a professionally fabricated board. For the professionally fabricated boards on the final design, the method of reflow soldering using a reflow oven was

implemented. Using the reflow method is faster and more accurate, especially for smaller components, in comparison to soldering by hand.

3   RESULTS

The overall design process proved to be very complex; however, the test plan demonstrated the most complexities. We attained results that met all requirements that will be explained in later sections, but first we will look at how we got to that point. Starting with a simple idea, this project evolved into a finished, fabricated project based on rigorous scheduling, extreme thoroughness, and cooperative efforts.

3.1   DESIGN PROCESS

Figure 7: Design & Test Process
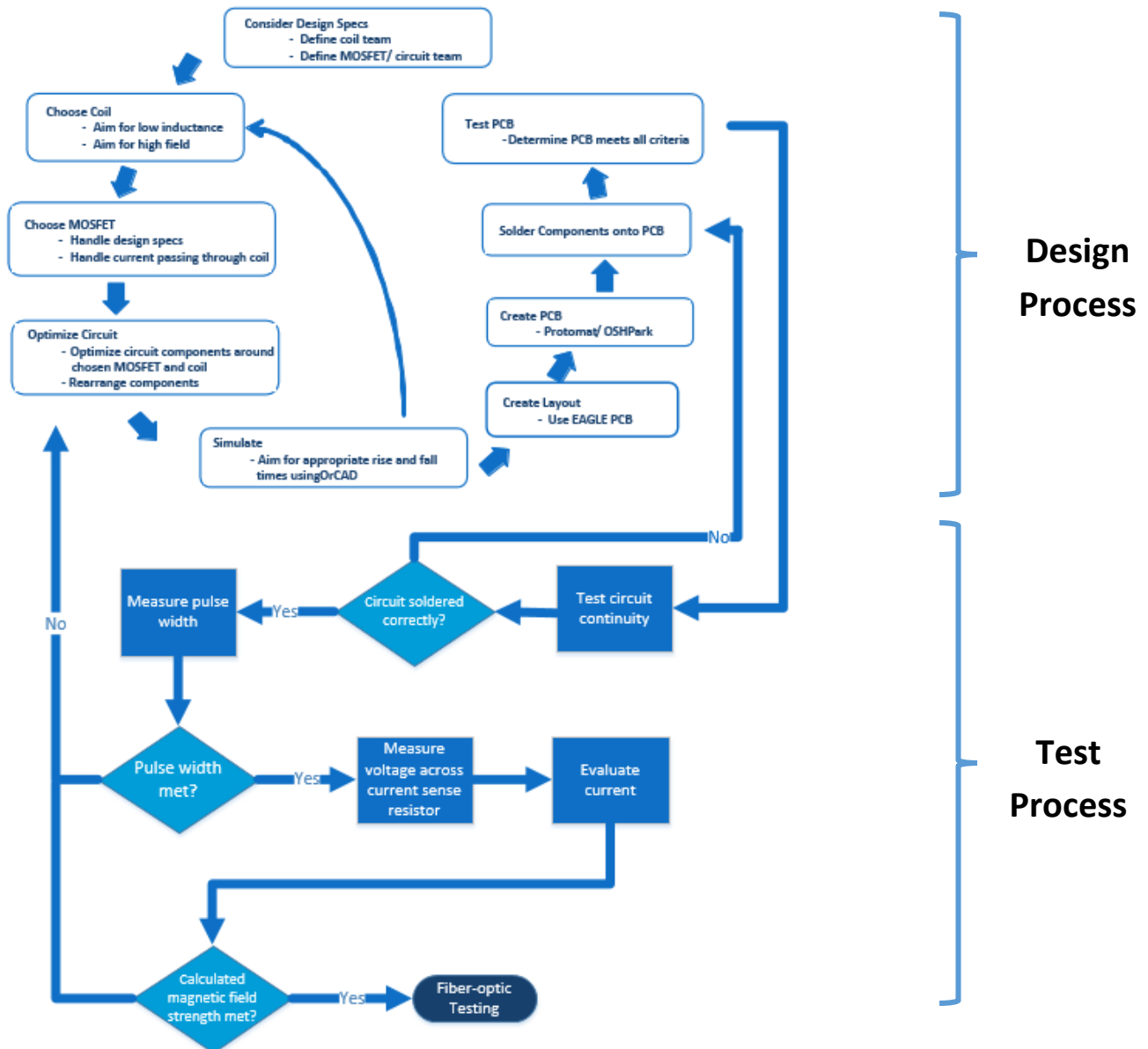
The design process and test process were integrated throughout the entire project. We started our design process by quickly realizing that the coil and MOSFET were going to be the two most important elements of the magnetic pulse generator. As explained in previous sections, the coil provides the magnetic field and the MOSFET is used as a switch. The members of our team split into two subset teams- coil and MOSFET/circuit teams. The coil team began research on the type, material, and inductance of various coils. The team focused on achieving low inductance in order to have a quick rise and fall time. Also, in order to meet our design requirement of reaching 500 gauss, the current, number of turns, and wire specifications needed to be evaluated. The MOSFET team created the circuit schematic in order to handle fast switching and high current. Optimization of circuit and addition of components that complemented the MOSFET and coil were next in the process. Simulation was done via OrCAD to verify appropriate rise and fall times. If we did not reach appropriate rise and fall times, the inductance of the coil needed to be lowered. Once rise and fall times were met in order to get our one microsecond pulse, the PCB layout was created. Fabrication and population of board were next. Once we had a functional board, the testing procedure began.
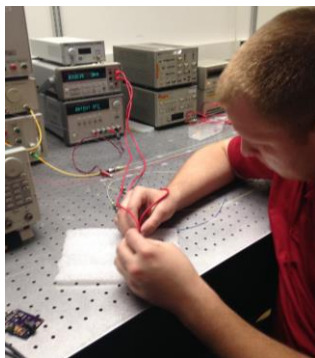
3.2   TEST PROCESS

Figure 8: Continuity Check

Testing was a key process in the second semester. Once the board was populated, a continuity check of the circuit was conducted as shown in figure 8. When components didn't pass the check, they were re-soldered. The one microsecond pulse width was the next obstacle to overcome. The rise and fall times needed to be quick in order to achieve this requirement. When a one microsecond pulse was generated, an oscilloscope measured the voltage crossing the current sense resistor. As previously discussed, the current through the current sense resistor is the same as the current through the coil. This current value was used in calculating the magnetic field.

Towards the end of testing, we realized just how difficult it was to be able to prove through testing (not just theoretically) that specifications were reached due to measuring instruments not able to read the magnetic field of such a short pulse. By testing using our client's Sagnac Interferometer setup, we were able to confirm proof of specifications met.

- Initial testing plan and procedure
- How we tested and treaded lightly at first
- Initial setbacks
- Cable issues
- Switching from manual to automated testing

3.3 SIMULATION

3.3.1 CIRCUIT SCHEMATIC

Shown below is the schematic of the magnetic pulse generating circuit. As you can see by the organization of components, this schematic closely follows the block diagram shown in the system description section above. This circuit was first created and simulated in OrCAD. Once we gained further understanding of other schematic software, we chose CadSoft EAGLE Layout Editor to create the final schematic as you see below. The MOSFET was chosen carefully, as this component was crucial in the ability to handle design specifications.
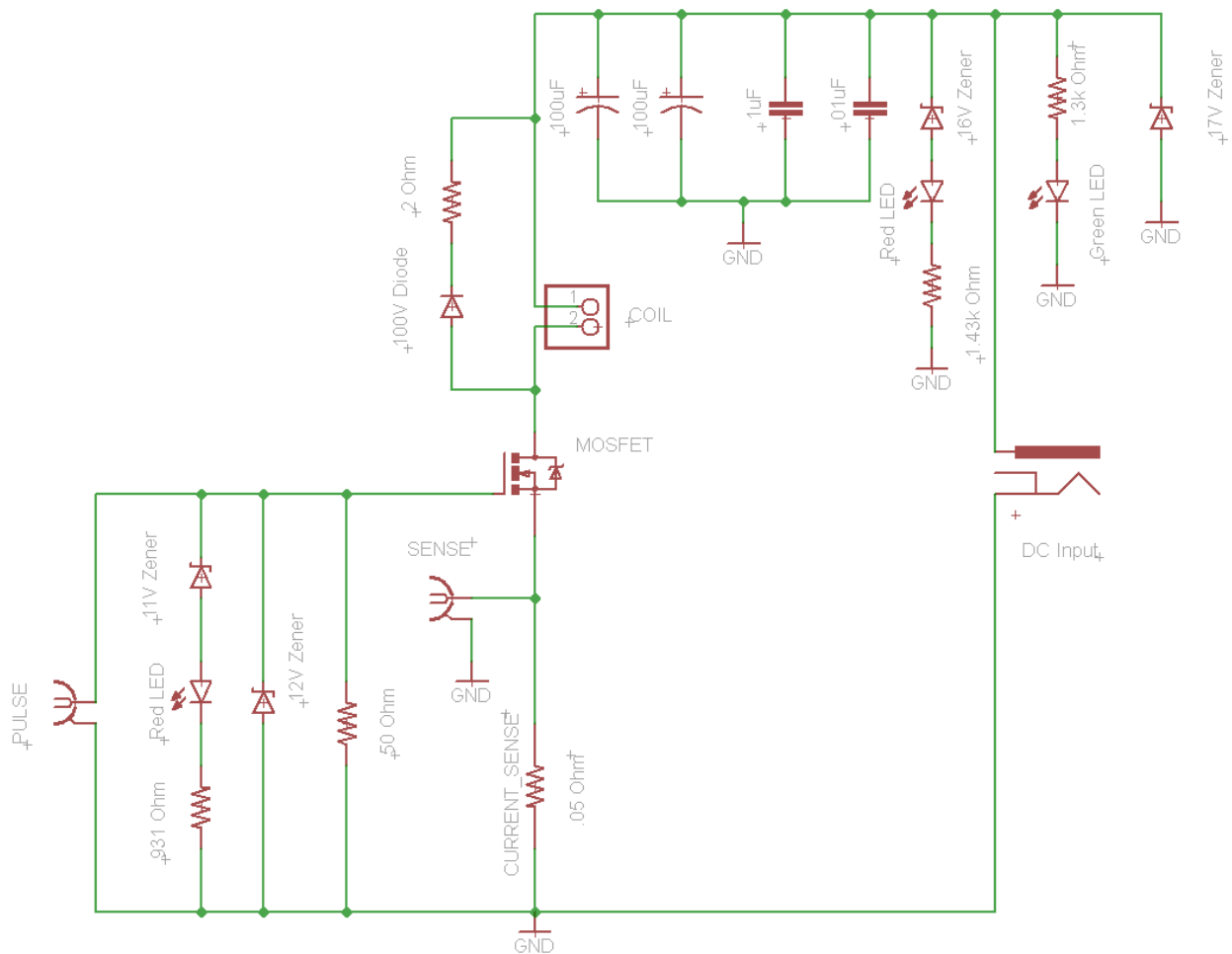
Figure 9: Circuit Schematic

3.3.2 SIMULATION RESULTS

After a basic circuit schematic was decided upon, the team moved to simulate the circuit using OrCAD software. Our first step was to decide on a MOSFET. The MOSFET that chosen based on fast switching speed to accommodate the one microsecond pulse width and be able to withstand a high current to generate the required magnetic field. Below figure 10 shows two MOSFETS that we were considering using in our circuit. The MOSFET spice files were obtained directly from the manufacturer's website.
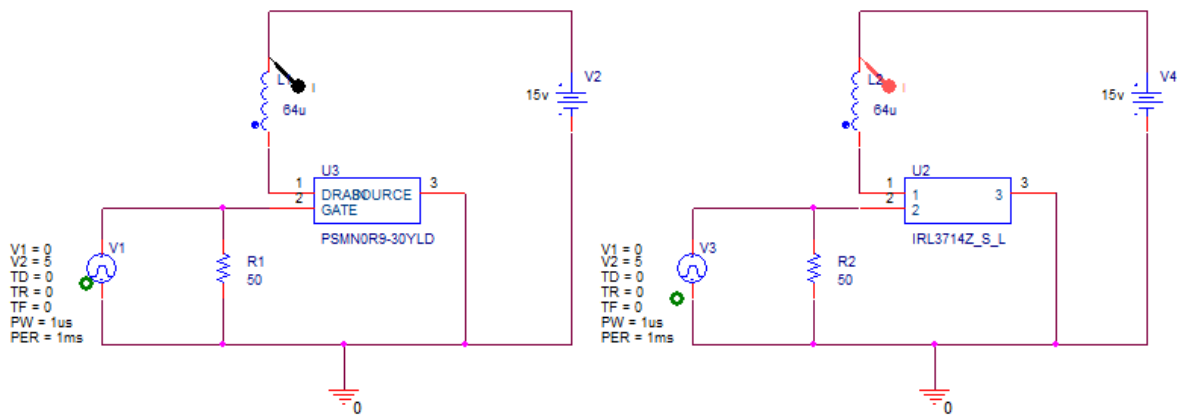
Figure 10: MOSFET Considerations

Once the simulation was ran we could see the individual results for the MOSFETs as how they react to the one microsecond pulse in conjunction with the coil. As you can see in the Figure 11 below, the left MOSFET performed better than the right one. We can see that in the faster rise time followed by the shorter fall time.
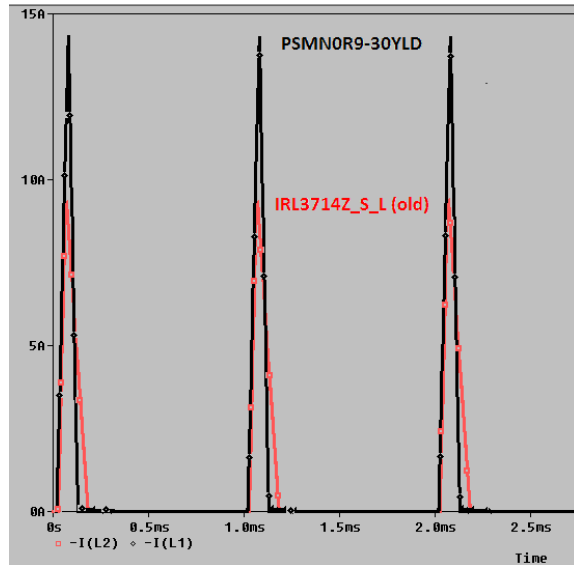
Figure 11: MOSFET Performance

After the MOSFET was chosen the simulation team worked with the coil team to determine the most appropriate coil to use. Once simulations began, it quickly became apparent that a smaller inductance in the coil would yield a smaller rise time. This is shown in this simulation where one inductor coil has twice the inductance as the other. It is important to note that the inductances are still very small, but have a large impact on our circuit.
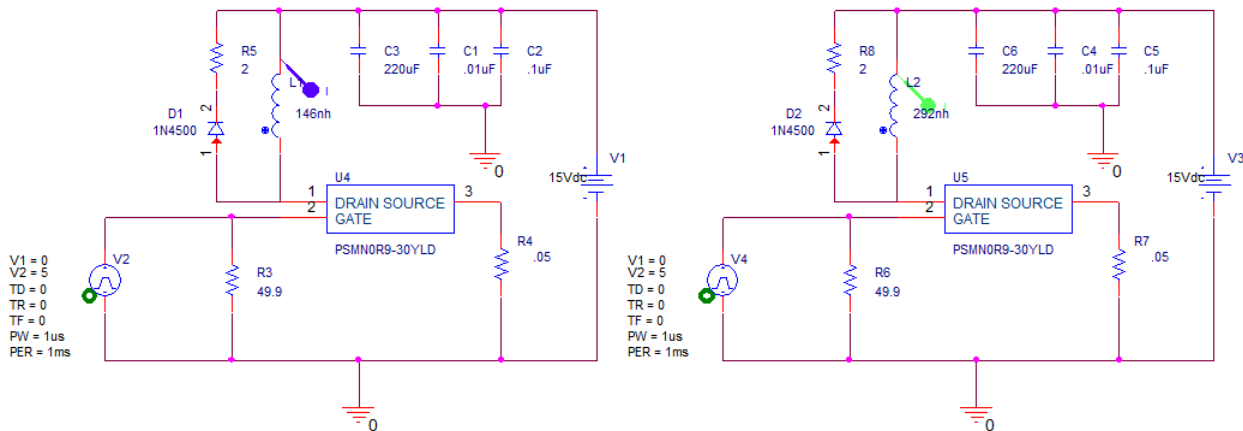
Figure 12: Inductance Effects on MOSFET

As shown in figure 13, the inductance of the left circuit is 146nH and the inductance on the right is 292nH. The circuit with the smaller inductance is represented by the purple line in Figure 13 below and the green line is the larger inductance.
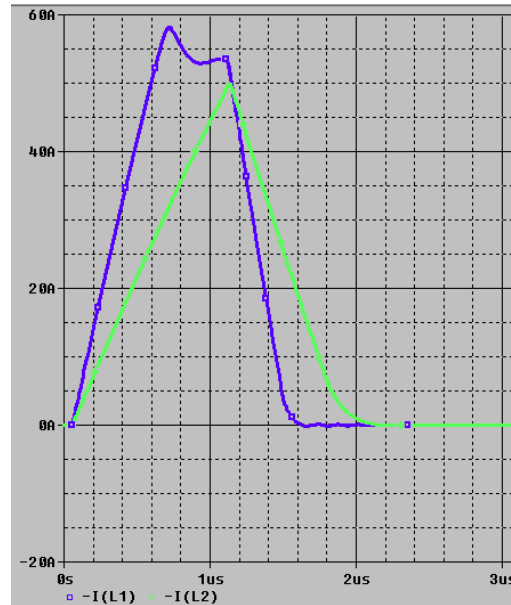
Figure 13: Pulse Width Measurements

As shown in figure 13 above, the smaller inductance (purple line) had a faster rise time then the larger inductance. This led us to decide that we needed a coil with a small inductance to minimize our rise time and maximize our magnetic field.

When simulating this circuit initially we saw that the fall time was extremely long and postulated that the long rise time was due to the fact that our coil was reenergizing itself as it discharged. To combat this we added a 2 ohm resistor to our feedback protection circuit. You can see it as R5 in the left circuit on Figure 14 below.
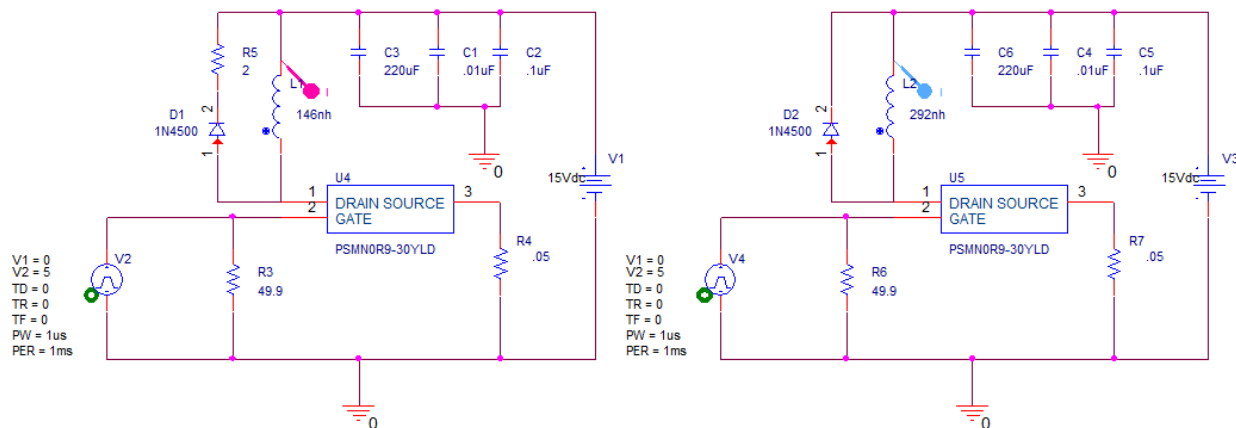
Figure 14: Testing with Back EMF Protection

The addition of the 2 ohm resistor decreased the fall time substantially as seen in figure 15 below.
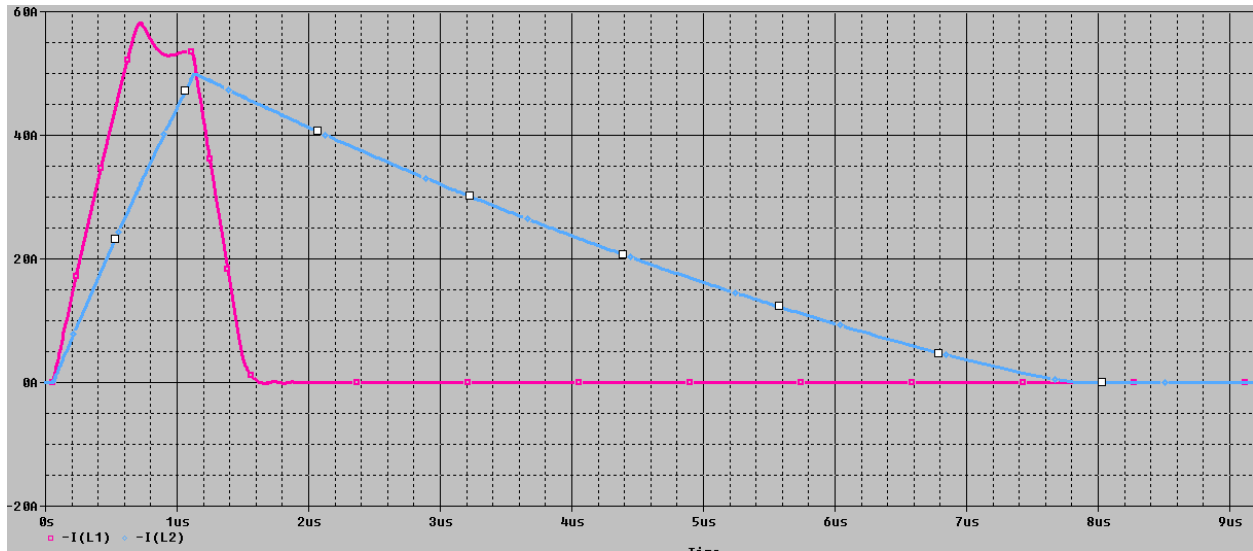
Figure 15: Resistor Effects on Fall Time

The circuit containing the resistor and diode in parallel with the coil is seen as the magenta line, while a circuit with only a diode in parallel is seen as blue.   The circuit containing the resistor in parallel with the coil de-energizes in a fraction of the time that circuit without does.

3.4   HARDWARE

3.4.1 PRINTED CIRCUIT BOARD

Figure 16 depicts the layout of the PCB using CadSoft EAGLE Schematic Editor. Appendix C illustrates previous designs from last semester that were altered into the layout you see before you here. The dimensions of this board meet our specifications, totaling: 2.0" (L) x 1.5" (W). As can be seen, each component on the board is labeled to make it user friendly. See Appendix A for the user guide for more information on the circuit board.
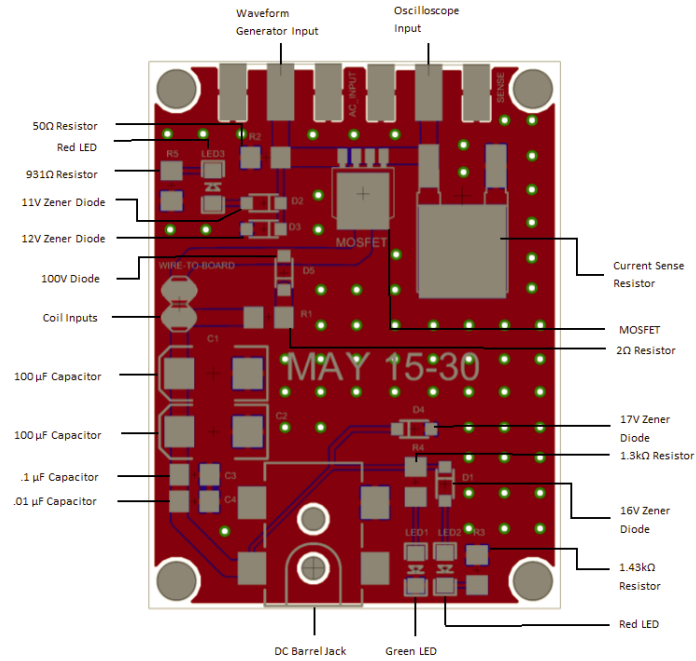
Figure 16: PCB Layout
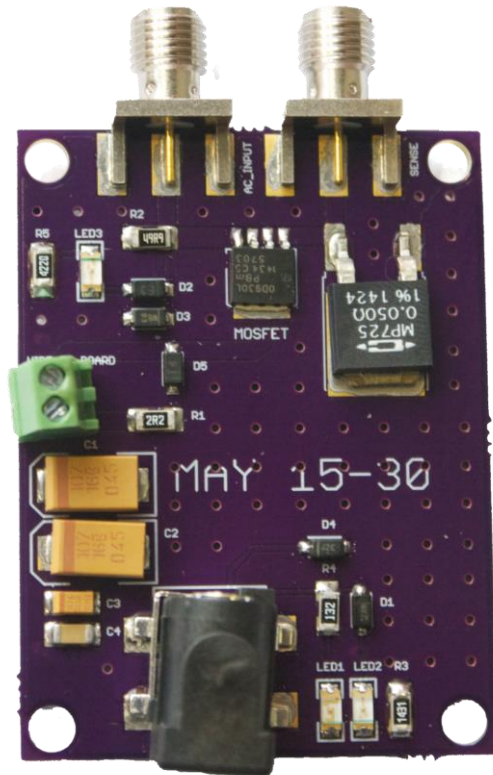
Figure 17: Populated Circuit

3.5   SYSTEM FEATURES

In addition to the required functions of the PCB, many features have been added to make it easy to use and understand in comparison to our initial designs. A DC Barrel Jack is included to allow the user to plug the DC voltage into the PCB. Board Edge SMA Connectors simplify the process of hooking the pulse input and oscilloscope. They also keep the wires out of the way of other components of the circuit. The green Wire to Board Connector is used as the input for the coil. This component allows for coils to be switched in and out. Throughout the board, you will find LEDs. The green LED indicates when the DC power supply is working. Two red LEDs indicate when the circuit may be in harm due to the voltage (either DC or AC) being set higher than the intended value.

3.6   DATA ANALYSIS

3.6.1   INITIAL TEST SETUP

To perform testing using the client's Sagnac interferometer setup, we needed to gain a better understanding of what the Sagnac interferometer does. Shown below in Figure 18 is the Sagnac interferometer. This setup is used to detect the magnetic field pulse. Conventional magnetic field detectors are not able to pick up the pulse fast enough because their sample rate is lower than the required 2 MHz we would need. The system will send out an optical signal that will split at a coupler and then interfere with itself, resulting in either constructive or destructive interference which will be measured at the output. The interference depends on the state of magnetization of the magneto-optic (MO) material. In one direction, we would measure no output, and when it is magnetized the other way we would see an output.
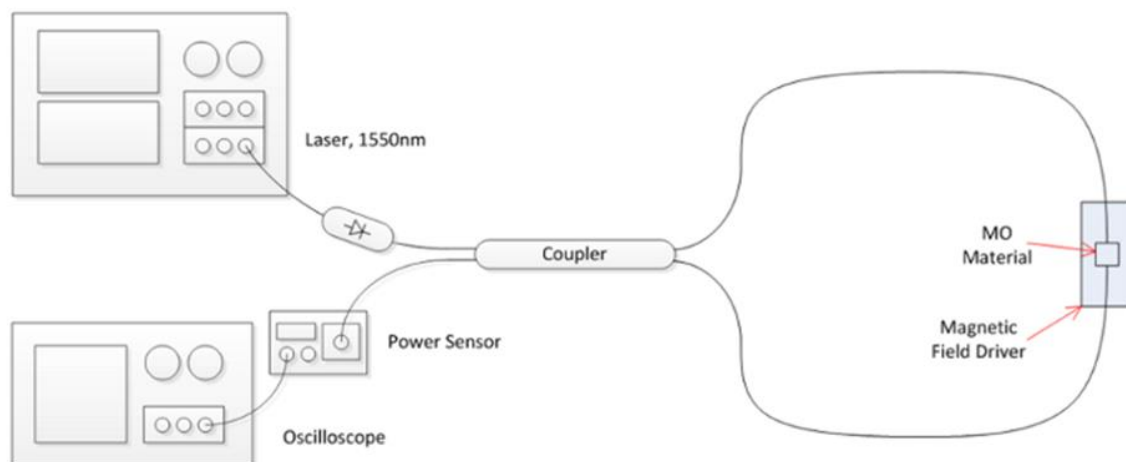
Figure 18: Sagnac Interferometer

As can be seen in Figure 18 above, the Magnetic Field Driver is located around the MO Material. This is where our circuit would be. The MO material is housed in a sheath between two optical connectors that are coupled together as shown in Figure 19 below. Our testing would measure the optical signal's power over a 360° range and then measure it again after pulsing our magnetic field to change the polarization of the MO material.
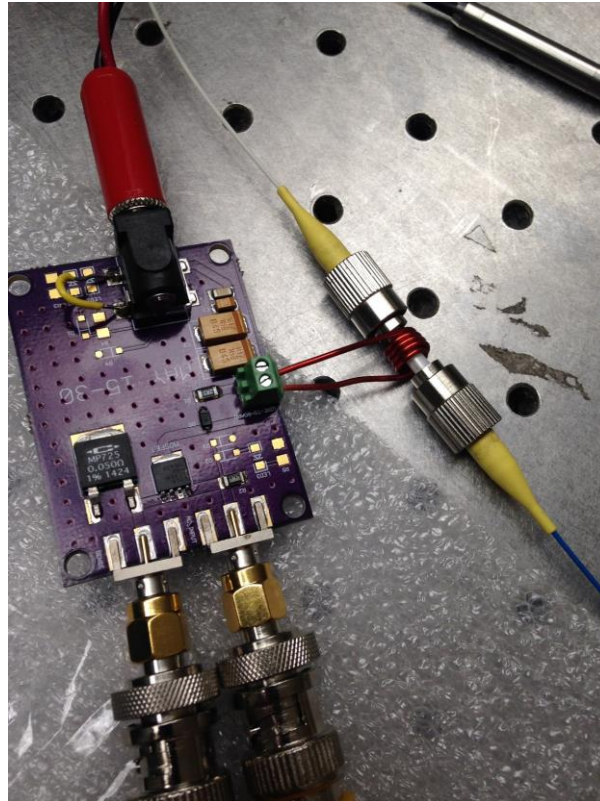
Figure 19: Sagnac Interferometer Configuration

3.6.2 INITIAL DATA

The important data for us to measure was that we could generate our pulse in 1 μs and also generate a field that was at least 500 G. Using a 15 V DC input, 1 μs pulse width input, 2 V_{p-p}, and coil C from section 1.3.6, we were able to obtain the following data shown in Figure 20 below. The results show that our pulse width was approximately 930 ns. By modifying the coil parameters, it is possible to increase or decrease this measurement.
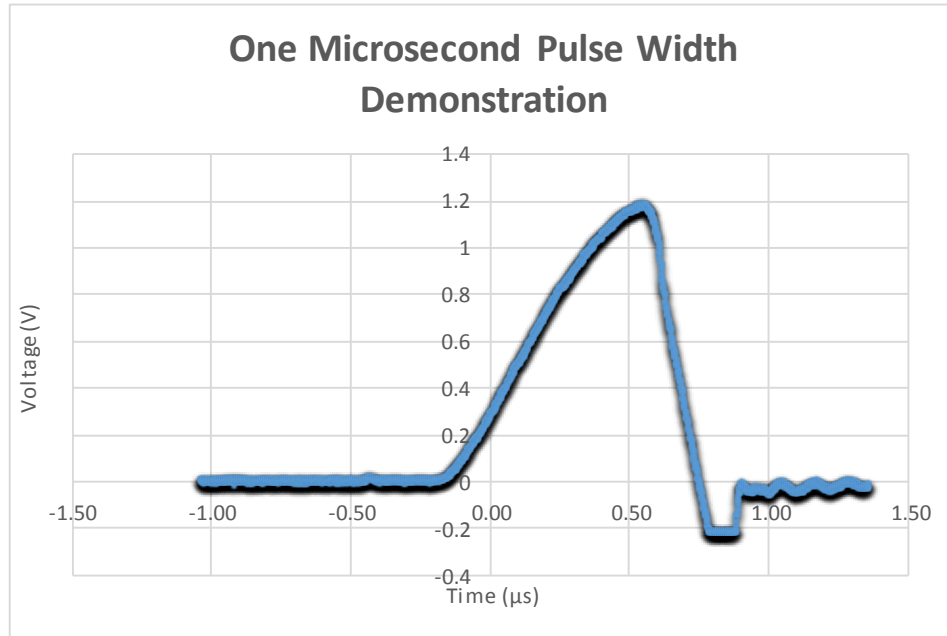
Figure 20: One Microsecond Pulse Width Demonstration

The results using the magneto-optic (MO) material our client wanted to use (Integrated Photonics, Inc. MGL Garnet – Latching Faraday Rotator) has a switching field $\geq$ 500 G at 22°C. That tells us that if we can obtain at least a 500 G field at approximately room temperature, we should see the polarization of the material change thus changing the power measured at the output. Using MATLAB scripts created by our client, we took a measurement before turning our circuit on, another measure after turning our circuit on, then combined the data to measure the phase shift to see if it is what we would expect. Below in Figure 21 are the results of our initial test showing we experienced virtually no phase shift.
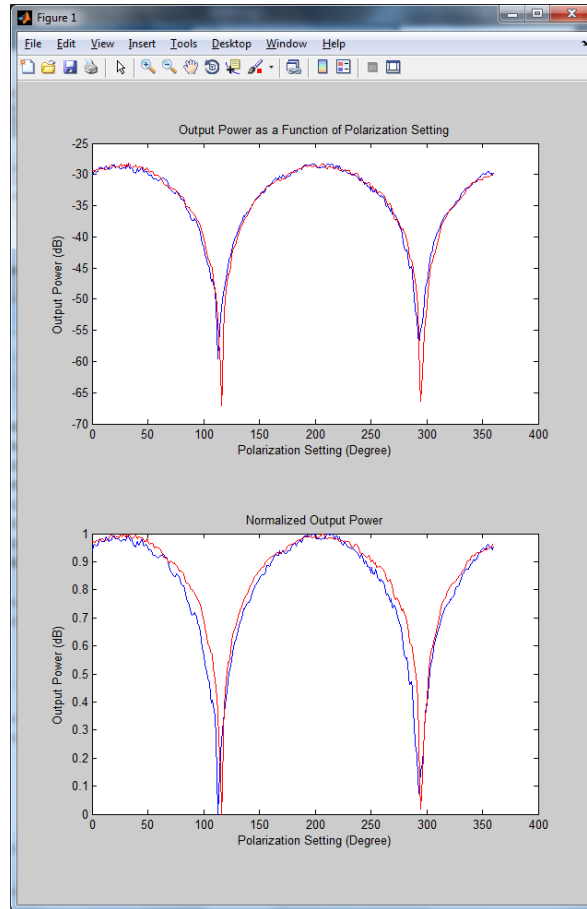
Figure 21: Output Power Phase Shift Measurement

At this point we knew either our circuit was not performing as intended or the MO material was not reacting as expected. This led us to develop a new test.

3.6.3 FINAL TEST SETUP

A new method was developed to demonstrate the functionality of our circuit that involved us making theoretical calculations on the field strength we could obtain by reducing our input parameters then performing a test on a magneto-optic (MO) material that could be affected by a smaller magnetic field strength. We would then use that data to determine if 500 G was attainable by scaling the parameters to their maximum values. The new MO material was the Integrated Photonics, Inc. FLM Garnet – Low Moment Faraday Rotator. This material operates differently than the MGL latching material does in the respect that it will reach a saturation point when the magnetic field strength exposed to it is ≥ 225 G. Using our magnetic field calculations and modifying our parameters, we were able to determine what we can set the parameters to in order to see the MO material saturate. Our measurements would be taken on the voltage across the current sense resistor (CSR) as well as the change in power of the optical signal while we pulse our magnetic field. To do this, we needed to increase the pulse width of

our signal. Our expectation was that once the MO material was saturated, the change in the power of the optical signal would be close to zero.

3.6.4   FINAL DATA

We were able to discover that when we set the function generator to create a pulsing waveform with an amplitude of 3 V_{p-p}, we observed saturation in the MO material as shown in Figure 22 below. The yellow line represents the voltage measured at our CSR, while the blue line is measuring the change in power of the optical signal. As stated previously, we observed this as the saturation point because of the behavior of the optical signal power showing no change.
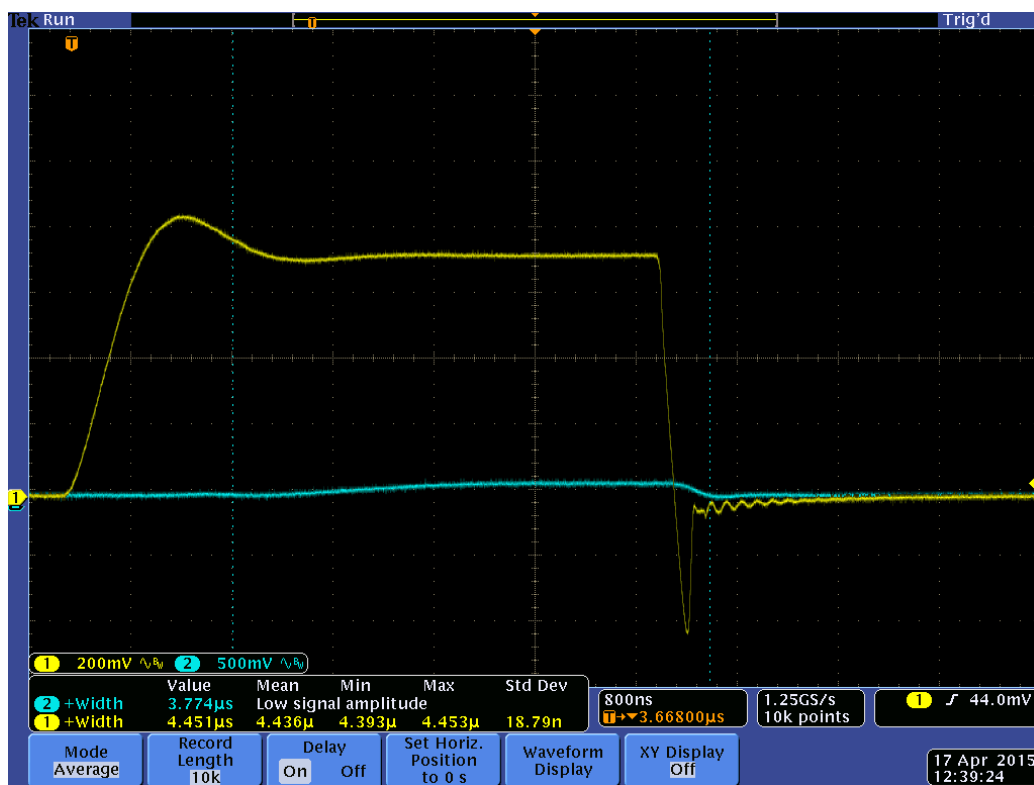
Figure 22: Saturation Observed

3.6.5   THEORETICAL VS ACTUAL

The results we obtained in our final testing demonstrated some abnormalities we did not expect to encounter. Based on the experimental results, our circuit saturated the magneto-optic (MO) material implying that a magnetic field strength of 225 G was obtained. Based on the parameters of our coil (length, radius, number of turns), the voltage measured across the current sense resistor, and the magnetic permeability, we obtain a theoretical value of

approximately 112 G. There are many factors that we knew could affect our theoretical calculations such as:

- The magnetic permeability may be larger due to us assuming that $\mu_r=1$
- The coil is not perfect (small gaps between turns, not perfectly aligned, etc.)
- The effects of the sheath housing the MO material
- Sensitivity of the MO material
- Human errors in measurements

This is an issue we are still working through currently. At this moment, although our theoretical calculations don't appear to demonstrate functionality, our circuit is performing to the satisfaction of our client.

3.7   IMPLEMENTATION ISSUES/CHALLENGES

3.7.1 SOLDERING SMALL COMPONENTS

Packaging sizes of the components ranged from a 0.01μF capacitor with the dimensions of 1.0 mm × 0.5 mm (0402) to a general purpose diode with the dimensions of 7.95 × 5.90 × 2.25 mm (DO-214AB (SMC)). With one of the requirements of the design being the size of the device, our first design measured 1.49" x 1.3". At that size and the sizes of the components, soldering of the components onto the board was difficult.

Figure 23: Small Component Example

3.7.2 TRACES LIFTING OFF

While soldering components onto the first board created from the ProtomatS62, the copper board used had traces that would lift off when removing the soldering iron after attempts to solder on a component. This issue was resolved when ordering a professionally fabricated board from OSHPARK.
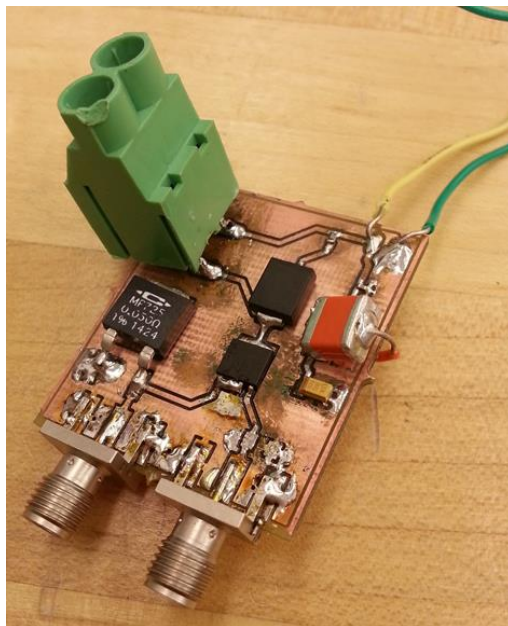
Figure 24: Effects of Repeated Soldering

3.7.3 HIGH CURRENT/ RISK OF BURNING COMPONENTS

The design of our circuit is focused on driving a large current, about 60 amps, though a coil in a short period of time (1 μs). This carried the inherent risk of overloading our circuit components and rendering them useless. Thus, all of our components were specifically chosen to be able to withstand a high current. Even though all of the components were chosen to be able to withstand a short burst of high amperage, care was still executed during testing. At one point during testing we were changing the pulse width to test the effects on our circuit output. When the pulse width was increased without increasing the period the MOSFET essentially remained on and our coil was overloaded due to continuous current being driven through it. After this incident, whenever the pulse width was changed, the period of the pulse was double checked.

3.7.4 COLD SOLDER

During the testing of the first design, a cold solder joint was discovered. Cold solder is where solder does not melt completely at the joint, therefore leaving a layer of oxidation in-between the component and the board. With that layer in-between the component and board the component was not connect to the board as assumed. To repair this issue the component was removed and re-soldered on.

3.7.5 DC BARREL JACK SCHEMATIC

While testing the second design, we discovered the DC barrel jack functioning contrary to how we expected. After looking at the datasheet, we determined pin A was our ground pin and pin B

was a wedge inside that indicates whether something is plugged in or not. After testing, we figured out we had installed the barrel jack incorrectly and the pins were mixed up. To solve our problem on current versions of our board, we simply jumped pin A and pin B together as we did not need the

functionality of the non-grounding pin. This issue is fixed on future layouts.
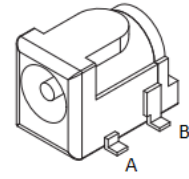
Figure 25: DC Barrel Jack Schematic

4 CONCLUSION

The goal of this project was to create a magnetic field generating circuit that could create a one microsecond pulse with a 500 gauss magnetic field. Our team's collection of circuit knowledge, EMF understanding, design process mindfulness, among other skills learned along the way, is shown in this descriptive document. This project was successful in providing the necessary requirements for the client as outlined in the 3.5 Data Analysis section of this document. We have completed this project with the utmost confidence the magnetic pulse generating device will be used in future applications.

5 APPENDIX A – USER MANUAL

5.1 OVERVIEW

5.1.1 COMPONENT LIST

Table 1: Component List

Designation	Description
C1	100 µF Capacitor
C2	100 µF Capacitor
C3	0.1 µF Capacitor
C4	0.01 µF Capacitor
D1	16V Zener Diode
D2	6V Zener Diode
D3	6.8V Zener Diode
D4	17V Zener Diode
D5	100V Diode
LED1	Green LED
LED2	RED LED
LED3	RED LED
R1	2Ω Resistor
R2	50Ω Resistor
R3	1.43kΩ Resistor
R4	1.30kΩ Resistor
R5	422Ω Resistor

5.1.2 PCB TOP LAYOUT
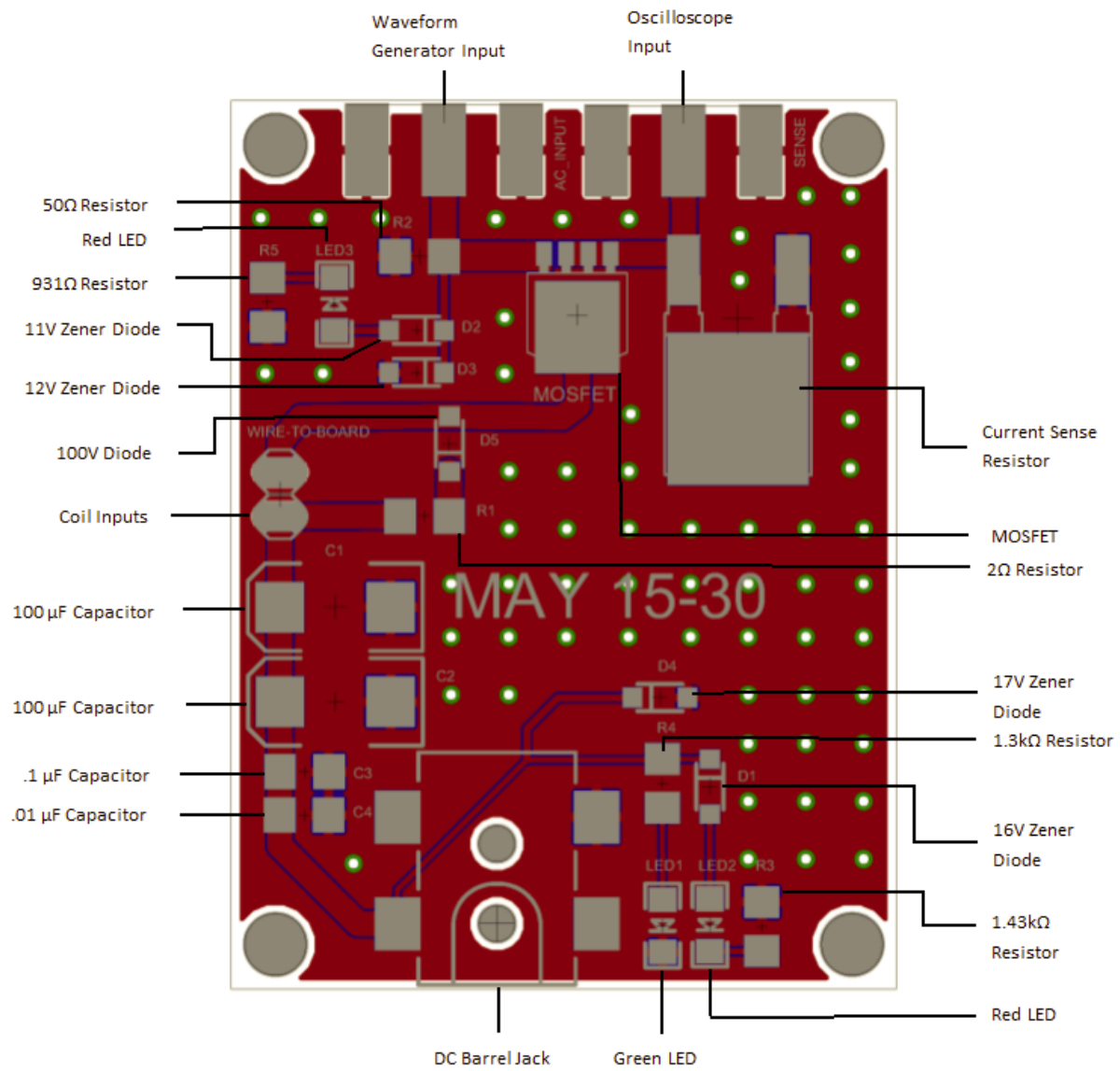
Figure 26: Partitioned Circuit Board

5.2   SETUP

Along with the PCB, you will need the following equipment to correctly set up the circuit:

- Coil
- DC Power Cable
- Oscilloscope and Probe
- SMA-SMA connectors (x2) with SMA-BNC Adaptors (x2)
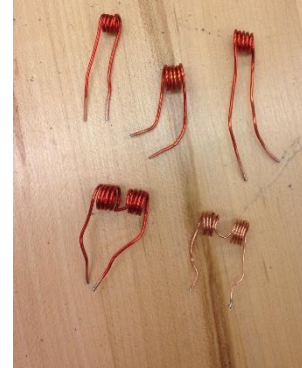
Figure 27: Coil Examples
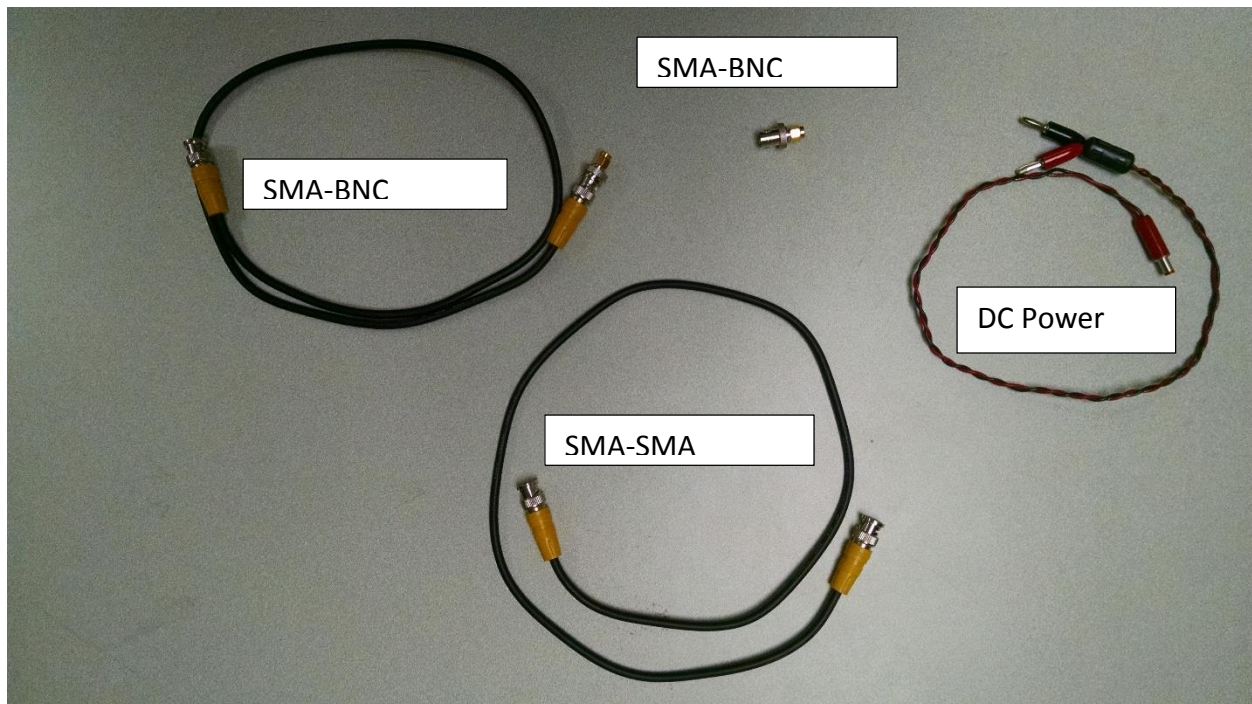
Figure 28: Cable Connector Examples

5.2.1 CONNECTING CABLES

To connect the PCB to the oscilloscope, DC supply, and waveform generator correctly:

1. Make sure DC supply and waveform generator are OFF
2. Insert and screw one lead of your coil in the left port of your wire to board terminal, and insert and screw the other lead of the coil in the right port

3. Connect 1 BNC-SMA adaptor on each of the SMA-SMA connectors, effectively creating 2 BNC-SMA connectors
4. Connect 1 BNC-SMA connector from the "Current_Sense" SMA on the PCB to the oscilloscope
5. Connect 1 BNC-SMA connector from the "AC_Input" SMA on the PCB to the waveform generator
6. Connect the DC Barrel Jack of the PCB to a DC supply using the DC Power Cable
    i.   DC supply must be able to output 15 VDC
    ii. When connecting to the DC supply, red is positive, black is negative

5.2.2 WAVEFORM GENERATOR AND DC SUPPLY SETUP

To properly configure the DC power supply and waveform generator to output what we are looking for:

1. Make sure DC supply and waveform generator are OFF
2. Set the DC supply to output 15 V, but keep it turned OFF
3. Set the Output Function to Pulse
4. Set the Run Mode to Continuous
5. Set the Output Load to be High Impedance
6. Set the Period
7. Set the Pulse Width
8. Set Low and High Amplitude
9. Set Leading and Trailing Edge

5.2.3 ERRORS AND INDICATION

There is one green LED to indicate whether the DC voltage source is on and functioning properly. There are also red LEDs to indicate when the voltage is set too high, and Zener diodes to redirect a portion of the current once the voltage is increased to a certain point. The red LEDs will come on if:

1. VDC is increased over 18V while the DC supply is ON
2. VAC is increased over 13V while the waveform generator is ON

6 APPENDIX B – ADDITIONAL INFORMATION

6.1   RESOURCES

Throughout the duration of this project, resources were used from Iowa State. A detailed list is shown below:

- Financial resources for parts, tools and supplies necessary to perform the research
  - Test and measurement equipment/software
  - Agilent 34410A Digital Multimeter
  - Tektronix DPO 4032 Digital Phosphor Oscilloscope
  - Tektronix AFG 3021B Single Channel Arbitrary/Function Generator
  - Agilent E3630A Power Supply
  - Hewlett Packard 8714ES RF Network Analyzer
  - Agilent 8164A Lightwave Measurement System
  - Agilent 8169A Polarization Controller
  - 1550nm Optical Laser Module
  - Optical Power Sensor Module
  - Lakeshore 410 Gaussmeter
  - Thorlabs DET10C Power Sensor
  - Transimpedance Amplifier
  - MATLAB Software License

6.2   LITERATURE SURVEY

This circuit can be used in many applications such as:

- Small-scale fiber optic switches and routers
- Megawatt Q-switched laser systems
- Research in biomagnetism
- Small solenoid systems

Although a single-coil field generator design is not a new area, few applications require small devices with such high current requirements at high speeds. With this said, little research has been done to create such a device.

J.W. Pritchard, M. Mina, R.J. Weber. (2013, July 7) *Magnetic Field Generator Design for Magneto-Optic Switching Applications* [Online]. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6558961

J.W. Pritchard, M. Mina, N.R.Y. Bouda. (2013) "Feel the pulse." *Magnetics Technology International*. [Online]. Vol. 2013, pages 04-07. Available:
http://viewer.zmags.com/publication/17fde0ad#/17fde0ad/6

Tioh, Jin-Wei, "Interferometric switches for transparent networks: development and integration" (2012). *Graduate Theses and Dissertations.* Paper 12487.

6.3   ACRONYMS

AC - Alternating Current

CAD - Computer-Aided Design

DC - Direct Current

EMF- ElectroMotive Force

LED - Light-emitting Diode

MO- Magneto-Optic

MOSFET - Metal-Oxide-Semiconductor Field Effect Transistor

PCB - Printed Circuit Board

TMS - Transcranial Magnetic Simulation

V_{p-p} – Voltage peak-to-peak

6.4   UNIT VARIABLES

B - Magnetic field of a coil [tesla], conversion: 1 tesla=10,000 gauss

μ - Permeability of free space, $4\pi \; x \; 10^{-7}$ [henries/meter]

N - Number of turn of a coil [dimensionless]

I -Current through a coil [amperes]

R - Radius of a coil [meters]

L - Inductance of a coil [henries]

l - Length of a coil [meters]

7   APPENDIX C –FIRST DESIGN

The original design of our circuit was created in EaglePCB and then fabricated on the Protomat S62. We chose this technique as it allowed us to make quick changes to the PCB and fabricate a new board in a timely manner. Shown below in Figure 29 are examples of some boards we created. Ultimately, these boards did not perform to the satisfaction we wanted. Between issues with soldering (weak traces, very small package sizes, etc.) and our desire to have a clean looking product, we ultimately re-designed our board and had it professionally fabricated.

Figure 29: Examples of Boards

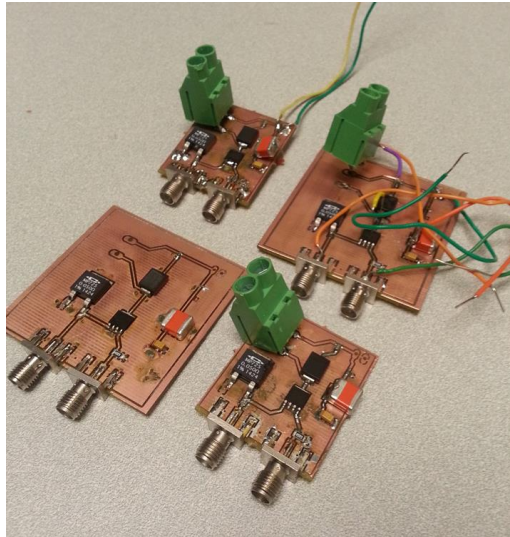As our knowledge of how our circuit needed to operate improved, we learned of various things we could improve in our circuit for our new design. We wanted to make the following changes:

- Increase the package sizes and make them more uniform
- Decrease the size of the wire-to-board connector
- Efficiently use the space on the board and don't maximize the dimensions if we don't need to use them all

8 APPENDIX D – BILL OF MATERIALS

Table 2: Total List of Parts Purchased

Quantity	Digi-Key Part Number	Item Description	Cost Per Unit	Total Cost	Vendor
10	497-6085-1-ND	Diode	$0.72	$7.22	Digi-Key
10	1N4148WTPMSCT-ND	General Purpose Diode	$0.14	$1.40	Digi-Key
10	MMSZ5233B-TPMSCT-ND	6V Zener Diode	$0.21	$2.10	Digi-Key
10	BZT52C6V8-FDICT-ND	6.8V Zener Diode	$0.21	$2.10	Digi-Key
10	BZT52C11-FDICT-ND	11V Zener Diode	$0.21	$2.10	Digi-Key
10	BZT52C12-FDICT-ND	12V Zener Diode	$0.22	$2.20	Digi-Key
10	BZT52C16-FDICT-ND	16V Zener Diode	$0.21	$2.10	Digi-Key
10	MMSZ5247BT1GOSCT-ND	17V Zener Diode	$0.24	$2.40	Digi-Key
6	MP725-0.050-FCT-ND	0.05Ω Current Sense Resistor	$9.13	$54.78	Digi-Key
10	P2.2ECT-ND	2.2Ω Resistor	$0.10	$1.00	Digi-Key
10	P49.9FCT-ND	49.9Ω Resistor	$0.10	$1.00	Digi-Key
10	P422FCT-ND	422Ω Resistor	$0.10	$1.00	Digi-Key
10	P931FCT-ND	931Ω Resistor	$0.10	$1.00	Digi-Key
10	P1.3KECT-ND	1.30KΩ Resistor	$0.10	$1.00	Digi-Key
10	P1.43KFCT-ND	1.43KΩ Resistor	$0.10	$1.00	Digi-Key
10	160-1169-1-ND	Green LED	$0.37	$3.70	Digi-Key
10	160-1167-1-ND	Red LED	$0.40	$4.00	Digi-Key
10	1276-2740-1-ND	0.01 µF Capacitor	$0.13	$1.30	Digi-Key
10	399-3677-1-ND	0.1 µF Capacitor	$0.38	$3.80	Digi-Key
10	399-3770-1-ND	100 µF Capacitor	$1.49	$14.90	Digi-Key
10	490-1312-1-ND	0.01 µF Capacitor (Ceramic)	$0.012	$0.12	Digi-Key
10	399-3677-1-ND	0.1uF Capacitor (Tantalum)	$0.329	$3.29	Digi-Key
4	718-1945-1-ND	220uF Capacitor (Tantalum)	$10.88	$43.52	Digi-Key
2	ED2675-ND	Wire-to-Board Connector (30A/300V Rating)	$1.04	$2.08	Digi-Key
14	J716-ND	Coaxial Connector	$4.84	$67.76	Digi-Key
4	ED10561-ND	Wire-to-Board Connector	$0.58	$2.32	Digi-Key
8	CP-002AHPJCT-ND	DC Barrel Jack	$1.89	$15.12	Digi-Key
6	N/A	PCB Fabrication	$5.00	$30.00	OSHPark
			Total Cost:	$274.31	

Table 3: Cost of Parts per Board Fabricated

Quantity	Digi-Key Part Number	Item Description	Cost Per Unit	Total Cost	Vendor
1	1N4148WTPMSCT-ND	General Purpose Diode	$0.14	$0.14	Digi-Key
1	BZT52C11-FDICT-ND	11V Zener Diode	$0.21	$0.21	Digi-Key
1	BZT52C12-FDICT-ND	12V Zener Diode	$0.22	$0.22	Digi-Key
1	BZT52C16-FDICT-ND	16V Zener Diode	$0.21	$0.21	Digi-Key
1	MMSZ5247BT1GOSCT-ND	17V Zener Diode	$0.24	$0.24	Digi-Key
1	MP725-0.050-FCT-ND	0.05Ω Current Sense Resistor	$9.37	$9.37	Digi-Key
1	RNCP1206FTD49R9CT-ND	49.9Ω Resistor	$0.10	$0.10	Digi-Key
1	P931FCT-ND	931Ω Resistor	$0.10	$0.10	Digi-Key
1	P1.3KECT-ND	1.30KΩ Resistor	$0.10	$0.10	Digi-Key
1	P1.43KFCT-ND	1.43KΩ Resistor	$0.10	$0.10	Digi-Key
1	P2.2ECT-ND	2.2Ω Resistor	$0.10	$0.10	Digi-Key
1	1276-2740-1-ND	0.01 µF Capacitor	$0.13	$0.13	Digi-Key
1	399-3677-1-ND	0.1 µF Capacitor	$0.38	$0.38	Digi-Key
2	399-3770-1-ND	100 µF Capacitor	$1.49	$4.47	Digi-Key
2	160-1167-1-ND	Red LED	$0.40	$0.80	Digi-Key
1	160-1169-1-ND	Green LED	$0.37	$0.37	Digi-Key
1	CP-002AHPJCT-ND	DC Barrel Jack	$1.89	$1.89	Digi-Key
2	J716-ND	SMA Connector	$4.84	$9.68	Digi-Key
1	ED10561-ND	Wire to Board Connector	$0.58	$0.58	Digi-Key
1	568-11554-1-ND	MOSFET	$1.79	$1.79	Digi-Key
1	N/A	PCB Fabrication	$5.00	$5.00	OSHPark
			Total Cost:	$30.84	

9   APPENDIX E – MATLAB CODE

9.1   SINGLE COIL CODE

9.1.1 MAGNETIC FIELD CALCULATION

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CurrentCalculationSingleShortCoil491.m ☒ BfieldCalculationSingleShortCoil491.m ☒ I_vs_N_table_Single.m ☒ +

```
1 -    clear all
2 -    close all
3 -    clc
4
5 -    N = input('How many turns are in the coil? ');          % N -> # of turns in the coil (dimensionless)
6 -    l = input('What is the length of the coil (in mm)? ');  % l -> length (meters)
7 -    R = input('What is the radius of the coil (in mm)? ');  % R -> radius of the coil (meters)
8 -    I = input('What is the current of the coil? ');         % I -> current (amperes)
9
10 -   B_T = ((4*pi*10^-7)*N*I)/sqrt((l*0.001)^2 + 4*(R*0.001)^2);   % Equation from MFG Design paper for single coil.
11 -   B_g = B_T*10^4;                                               % Converting magnetic field units: from Tesla to gauss.
12
13 -   disp(['The magnetic field generated with those parameters for a single short coil is ', num2str(B_g), ' Gauss.']);
14
```

9.1.2 CURRENT CALCULATION

yfiles ▸ megsharp ▸ Documents ▸ MATLAB ▸ EE492

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CurrentCalculationSingleShortCoil491.m ☒ BfieldCalculationSingleShortCoil491.m ☒ I_vs_N_table_Single.m ☒ +

```
1 -    clear all
2 -    close all
3 -    clc
4
5 -    N = input('How many turns are in the coil? ');               % N -> # of turns in the coil (dimensionless)
6 -    l = input('What is the length of the coil (in mm)? ');       % l -> length (meters)
7 -    R = input('What is the radius of the coil (in mm)? ');       % R -> radius of the coil (meters)
8 -    B_g = input('What is the magnetic field (in Gauss) of the coil? ');   % B_g -> magnetic field produced by the coil (Gauss)
9
10 -   B_T = B_g *10^-4;                                        % Converting magnetic field units: from Gauss to Tesla.
11 -   I = (B_T*sqrt((l*.001)^2 + 4*(R*.001)^2))/((4*pi*10^-7)*N);   % Equation from MFG Design paper for single coil.
12
13 -   disp(['The current required to generate that field for a single short coil is ', num2str(I), ' Amps.']);
14
```

9.1.3 PARAMETERS OF 500 GAUSS: CURRENT/INDUCTANCE VS. NUMBER OF TURNS

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| CurrentCalculationSingleShortCoil491.m ✕ | BfieldCalculationSingleShortCoil491.m ✕ | I_vs_N_table_Single.m ✕ | + |

```matlab
1    l = input('What length do you want to work with?');
2    %num_rad = input('How many radii do you want to enter try?');
3    %r(num_rad)=0;
4
5    %for k = 1:1:num_rad
6      r = input('What radius do you want to graph (in mm)?');
7    %end
8
9    N = [1:1:20];
10   I = zeros(1,20);
11   L = zeros(1,20);
12
13   %for j = 1:num_rad
14     for i = 1:1:20
15       I(i)= (0.05*sqrt((l*0.001)^2 + 4*(r*0.001)^2))/((4*pi*10^-7)*N(i));
16       L(i)= 1000*((((4*pi*10^-7)*(N(i))^2)*(pi*r^2))/(sqrt((l*0.001)^2+4*(r*0.001)^2)));
17     end
18     %figure(j)
19     %grid on
20     hold on
21     [hAx,h1,h2] = plotyy(N,I,N,L);
22     %str = sprintf('Turns vs. Current Single Short Coil: R = %fmm', r);
23     title('Single Coil 500 Gauss Parameters');
24     xlabel('# of Turns'); %xlim([0,50]);
25     ylabel(hAx(1),'Current (Amps)'); %ylim([0,100]);
26     ylabel(hAx(2),'Inductance (nH)');
27     legend([h1,h2],'Current','Inductance');
28   %end
```

9.2   HELMHOLTZ CODE

9.2.1 MAGNETIC FIELD CALCULATIONS

```matlab
1 -     clear all
2 -     close all
3
4 -     N = input('How many turns are in the coil? ');          % N -> # of turns in the coil (dimensionless)
5 -     R = input('What is the radius of the coil (in mm)? ');   % R -> radius of the coil (meters)
6 -     I = input('What is the current of the coil in Amps? ');  % I -> current of the coil (amperes)
7
8 -     B_T = (4*pi*10^-7)*0.7155*N*I/(R*0.001);                % Equation from MFG Design paper for a Helmholtz coil.
9 -     B_g = B_T * 10^4;                                       % Converting magnetic field units: from Tesla to gauss.
10
11 -    disp(['The magnetic field generated with those parameters for a Helmholtz coil is ', num2str(B_g), ' Gauss.']);
12
13      % To verify the equation used above we did a dimensional analysis:
14      %       u*N*I
15      % B =   -----
16      %        R
17      % UNITS:
18      % B -> Tesla(T) -> V-s/A*m
19      % u -> H/m -> Wb/A*m -> V-s/A*m
20      % N -> dimensionless
21      % I -> Amperes(A)
22      % R -> radius(m)
23      % V-s    V-s/A*m * A    V-s/m    V-s
24      % --- = ----------- = ----- = ---
25      % m^2        m           m      m^2
26
27      % Then we found that 1 Gauss = 0.0001 Tesla
```

9.2.2 CURRENT CALCULATIONS

cyfiles ▸ megsharp ▸ Documents ▸ MATLAB ▸ EE492

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BfieldCalculationHelmholtzCoil491.m ☒ | CurrentCalculationHelmholtzCoil491.m ☒ | I_vs_N_table_Helmholtz.m

```matlab
1 -     r = input('What radius do you want to graph (in mm.)?');
2
3 -     N = [1:1:20];
4 -     I = zeros(1,20);
5 -     L = zeros(1,20);
6
7       %for j = 1:num_rad
8 -     for i = 1:1:20
9 -         I(i) = (0.05*r*.001)/(N(i)*4*pi*10^-7*0.7155);
10 -        L(i) = 1000*((2*(4*pi*10^-7))*(0.7155)*(N(i))^2*pi*(r*0.001));
11 -     end
12      %figure(j)
13 -      hold on
14 -     [hAx,h1,h2] = plotyy(N,I,N,L);
15      %str = sprintf('Turns vs. Current Single Short Coil: R = %fmm', r);
16 -     title('Helmholtz Coil 500 Gauss Parameters');
17 -     xlabel('# of Turns'); %xlim([0,50]);
18 -     ylabel(hAx(1),'Current (Amps)'); %ylim([0,100]);
19 -     ylabel(hAx(2),'Inductance (nH)');
20 -     legend([h1,h2],'Current','Inductance');
21      %end
```